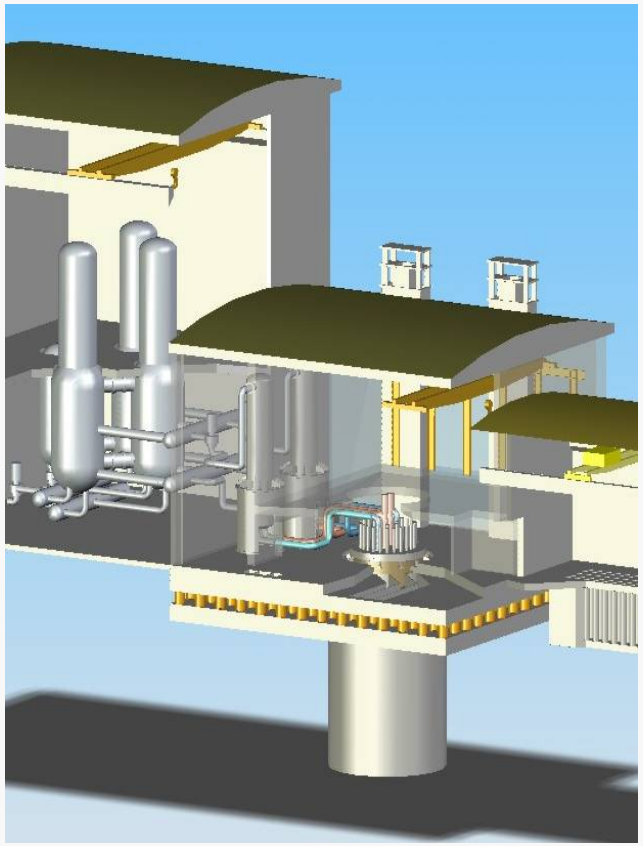
Alternative Passive Decay-Heat Systems for the Advanced High-Temperature Reactor

Charles W. Forsberg



International Congress on Advanced Nuclear Power Plants: Embedded Topical within the 2006 American Nuclear Society Annual Meeting
Session: 3.08: Liquid-Salt-Cooled High-Temperature Reactors II
Thursday, June 8, 2006
Reno, Nevada

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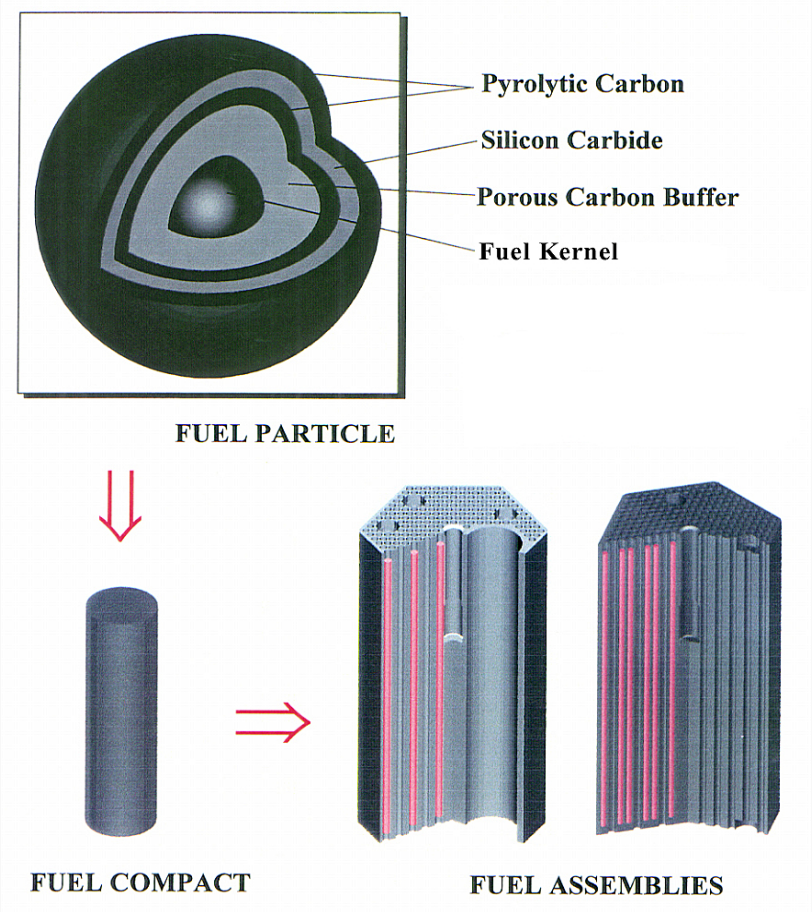
High-Temperature Reactors (HTRs)

High-Temperature Reactors Use Graphite-Matrix Coated-Particle Fuel

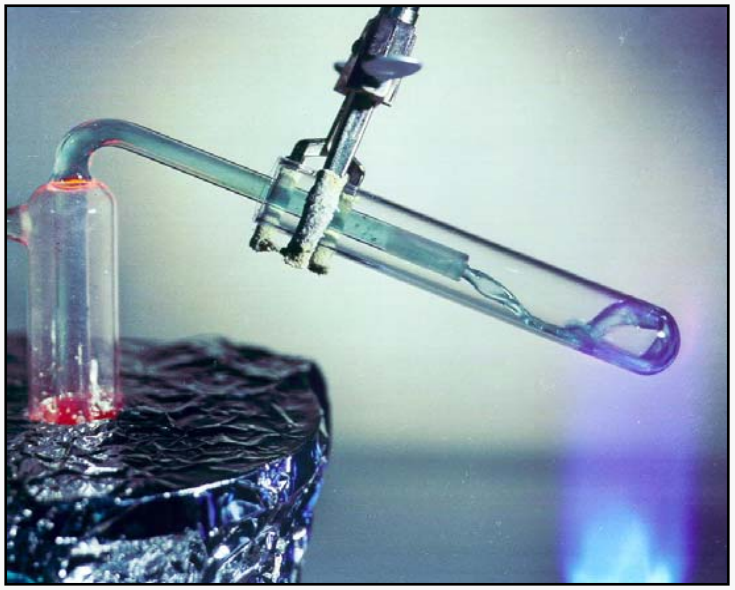
- **Fuel encapsulated in multilayer microspheres**
  - **Carbon layers**
  - **Silicon carbide layers**
- **Microspheres in a graphite matrix**
- **Only demonstrated high-temperature capability**
  - **Operating temperatures to 1200ºC**
  - **Accident capability to ~1650°C for limited time**



Two Reactor Coolants are Chemically Compatible with Graphite-Matrix Fuel

Modular High-Temperature Gas-Cooled Reactor

Advanced High-Temperature Reactor



Helium

(High Pressure/Transparent)

Liquid Fluoride Salts

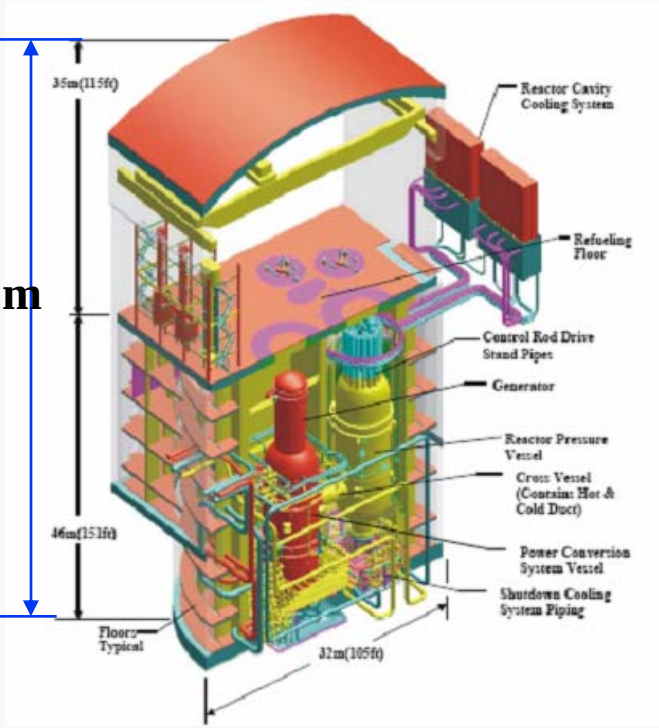
(Low Pressure/Transparent)

Two Reactor Options Based on Choice of Coolant

Two Types of High-Temperature Reactors are Being Developed

(MHTGR: Near Term; AHTR: Medium Term)

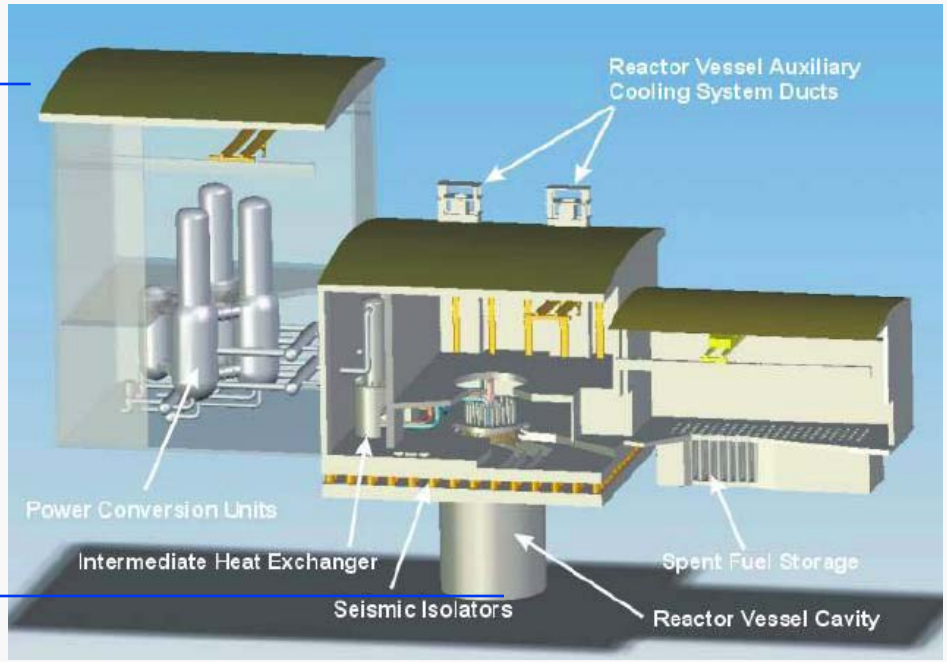
81 m



Modular High-Temperature Gas-Cooled Reactor

Gas Cooled: 600 MW(t); Near-Term Option

70 m



Advanced High-Temperature Reactor

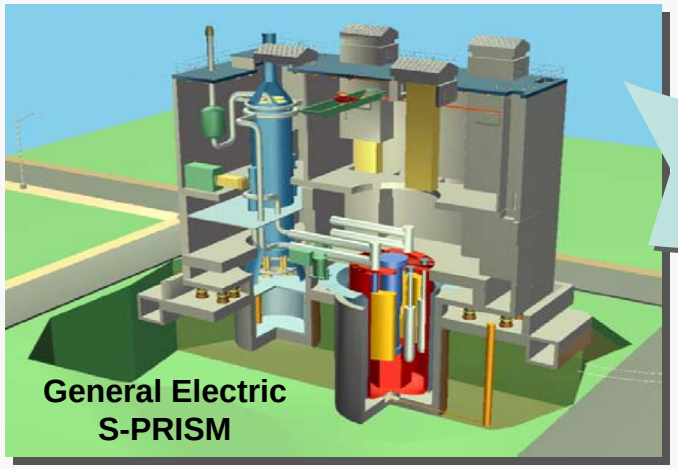
Liquid Salt Cooled: 2400 MW(t); Medium-Term Option

Per Peterson (Berkeley): American Nuclear Society 2004 Winter Meeting

The Advanced High-Temperature Reactor (AHTR)

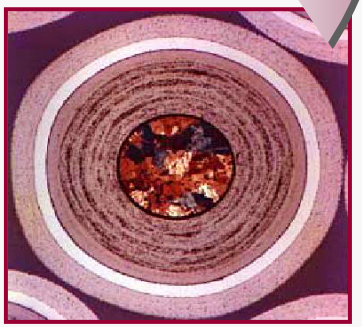
The Advanced High-Temperature Reactor

Combining Four Existing Technologies in a New Way



Passively Safe Pool-Type Reactor Designs

Brayton Power Cycles

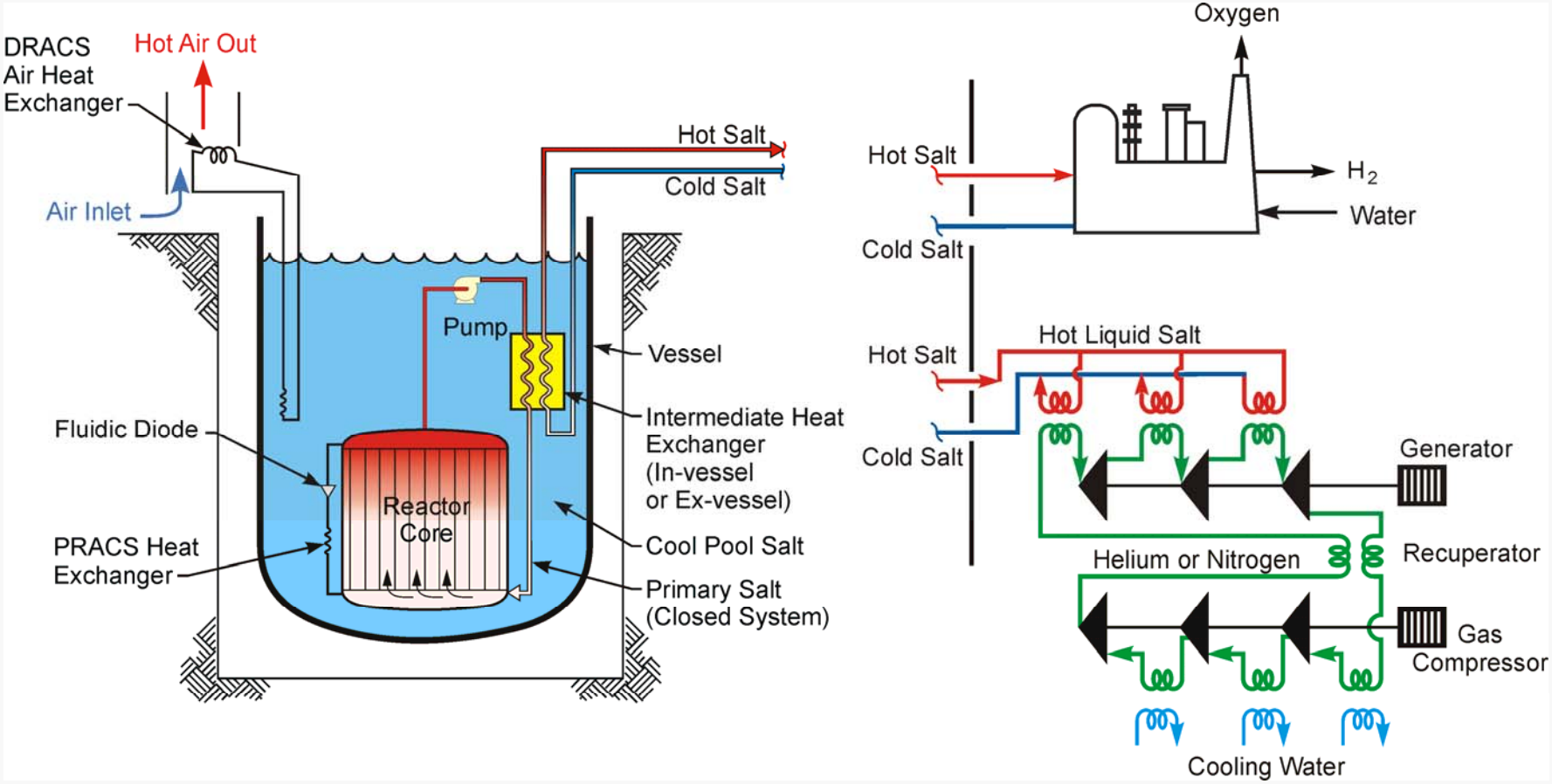


High-Temperature Coated-Particle Fuel

High-Temperature, Low-Pressure Transparent Liquid-Salt Coolant

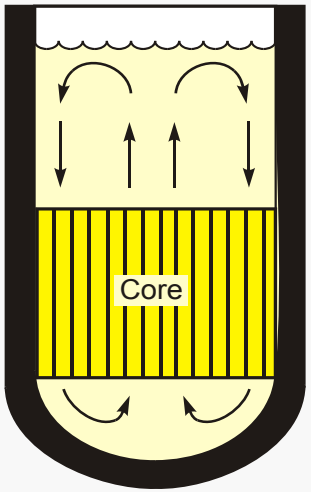
The Advanced High-Temperature Reactor

Passive Decay Heat Removal **Reactor** **Hydrogen/Brayton Electricity Production**



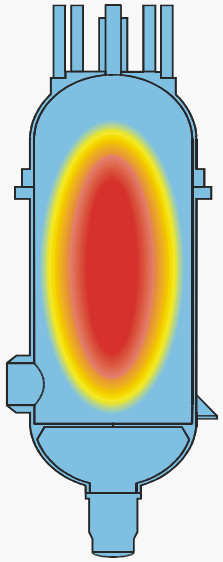
Liquid Cooling Allows Large Reactors with Passive Decay Heat Removal

Liquid
[1000s of MW(t)]



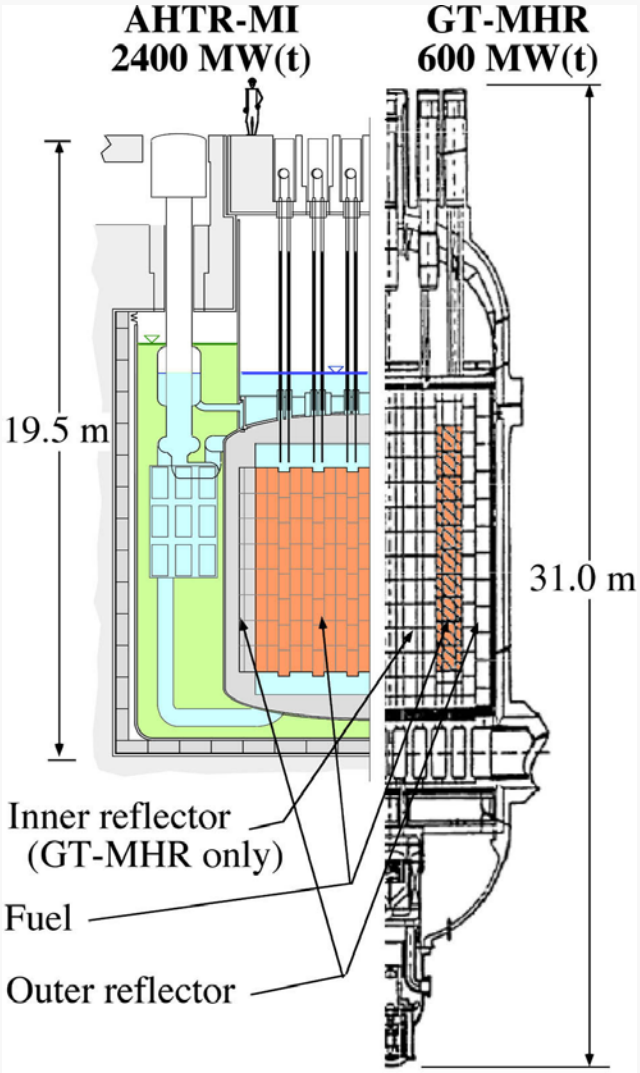
Decay Heat Removal Limited by Convective Cooling
(Added benefit of full use of internal heat capacity)

Gas
[~600 MW(t)]



Decay Heat Removal Limited by Conduction Cooling

AHTR Goals: Superior Economics While Matching Gas-Cooled HTR Performance

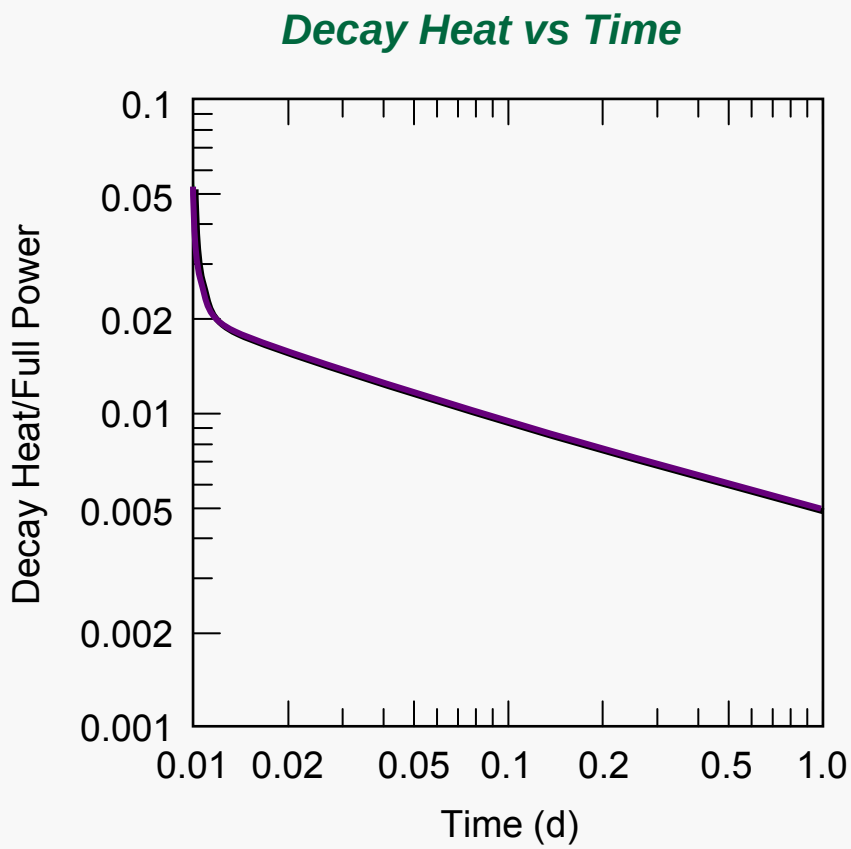


- **AHTR economic goal is a large reactor with superior economics**
  - **Capital costs 50 to 60% of those for modular reactor per kW(t)**
  - **Size: 2400 to 4000 MW(t)**
- **AHTR decay-heat-removal system requirements**
  - **Match passive safety of modular gas-cooled reactors**
  - **Match temperature of delivered high-temperature heat**
  - **Large reactor**

Alternative AHTR Passive Decay-Heat-Removal Systems

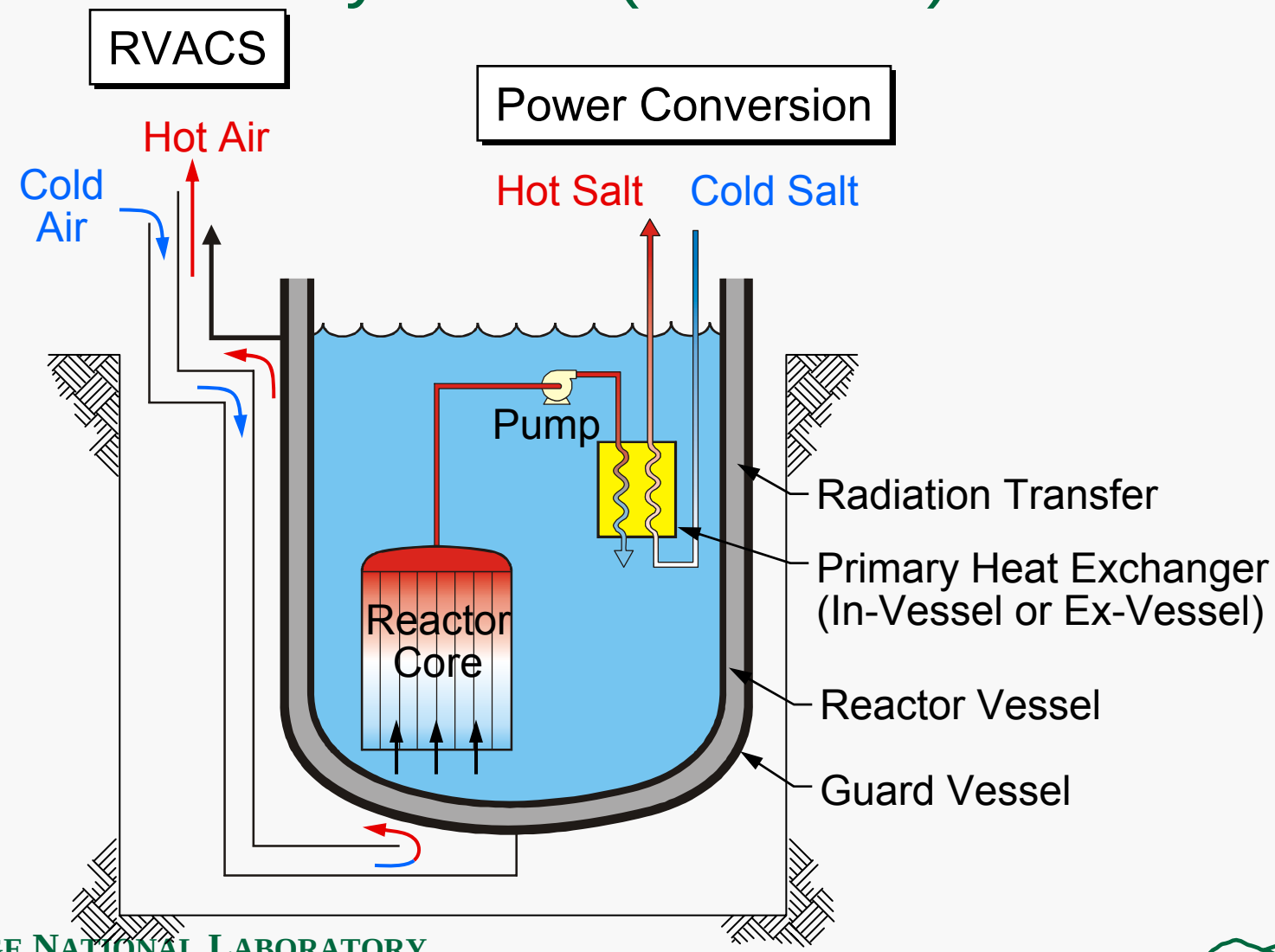
Three Options Identified

Decay-Heat Systems Have Several Strategies to Avoid SNF Overheating

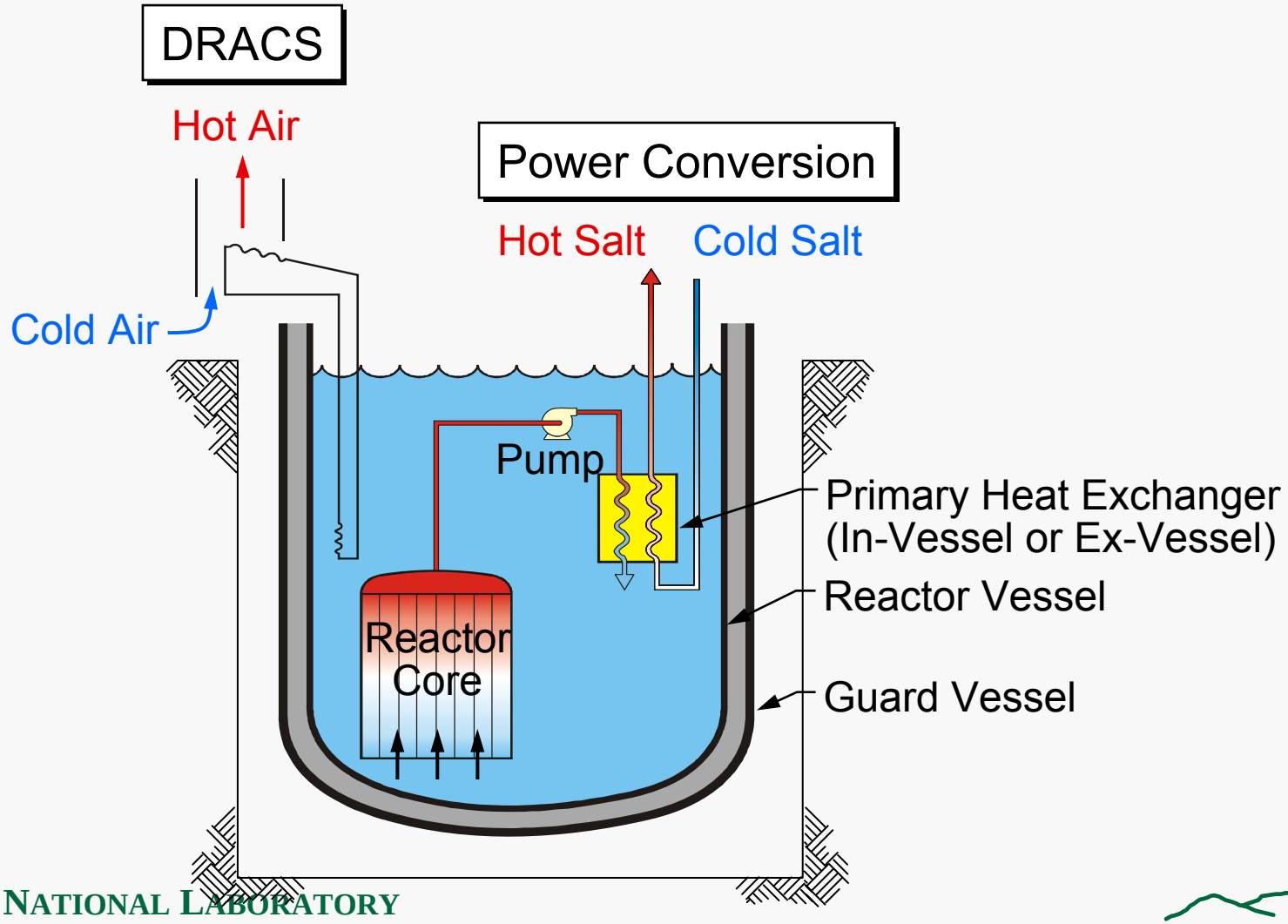


- **High heat-capacity system**
  - **Short-term decay heat management**
  - **Time for repairs**
  - **Reduced size of long-term heat removal system**
  - **Reduced sensitivity to the details of initiating event**
- **Long-term decay-heat removal to environment**

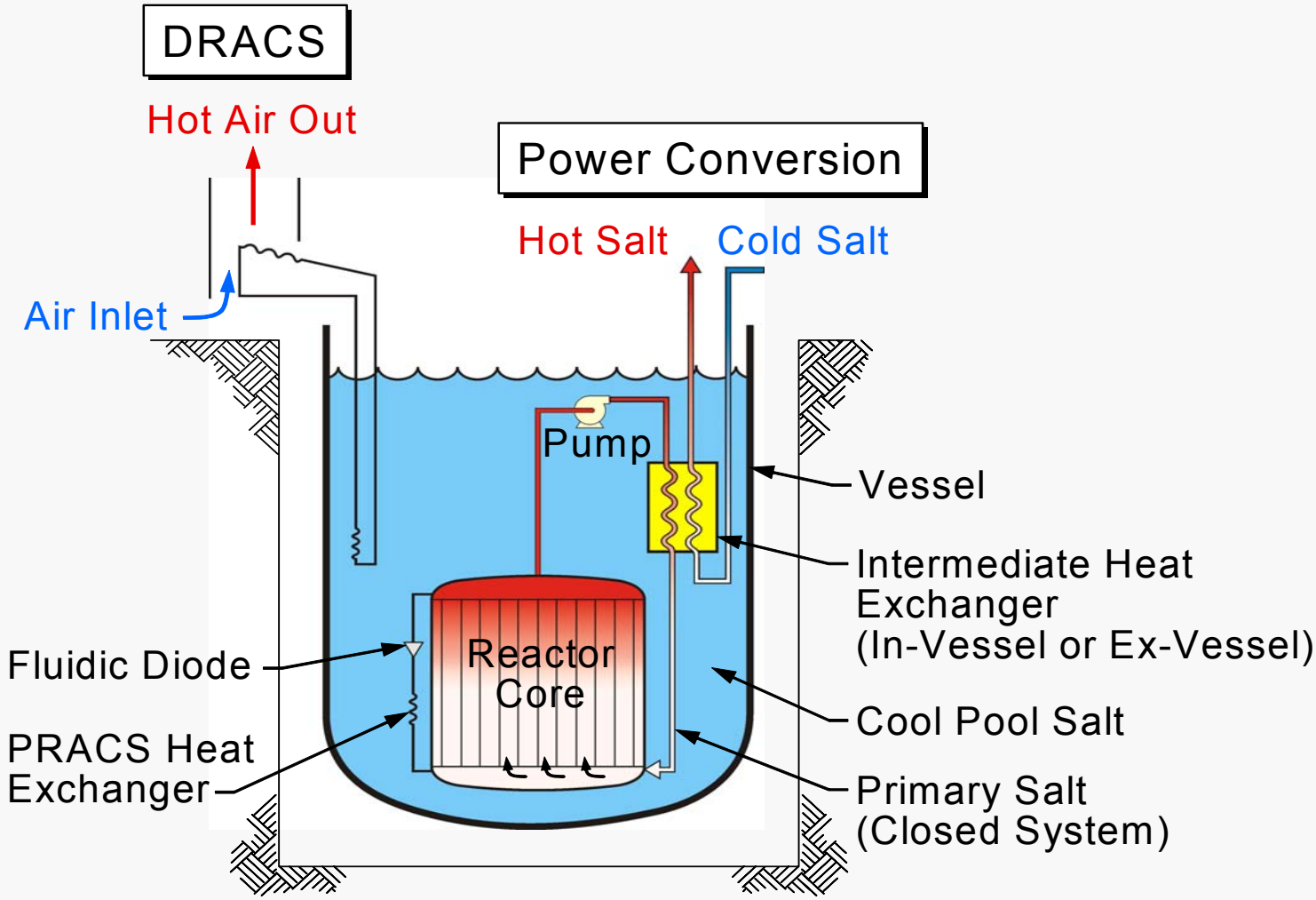
Reactor Vessel Auxiliary Cooling System (RVACS)



Direct Reactor Auxiliary Cooling System (DRACS)

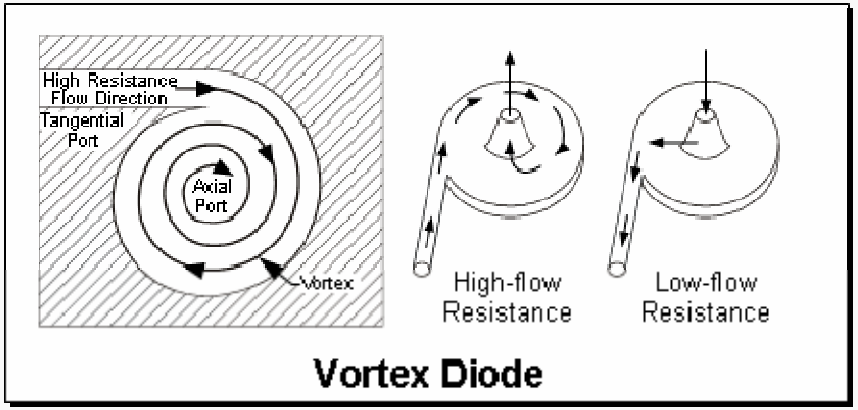


Pool Reactor Auxiliary Cooling System (PRACS)

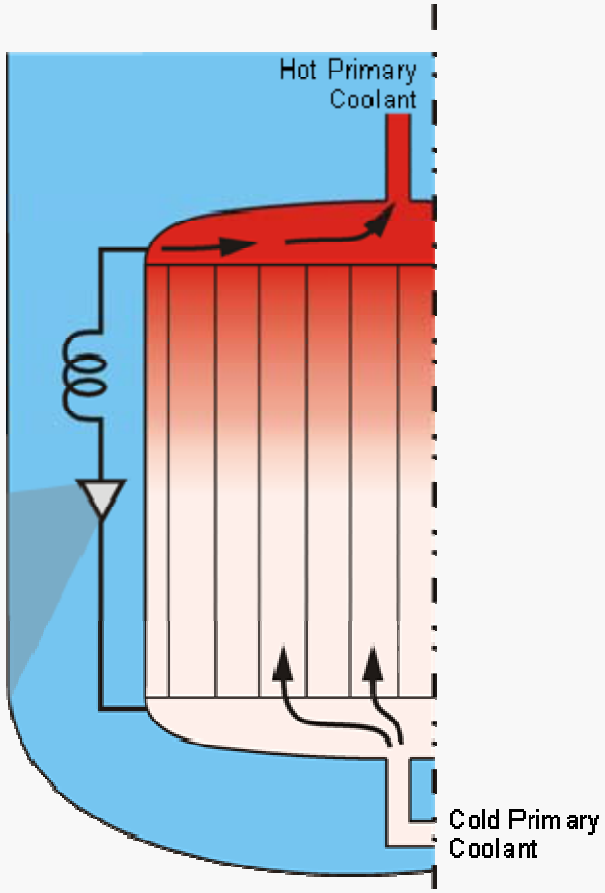


PRACS Heat Exchanger and Valve Dumps Decay Heat to the Pool Salt

- **Low flow in upward direction during normal operations**
- **High flow in reverse direction after pump shutdown and natural circulation flow startup**
- **Flow resistance 50 times higher in one direction than the other**



Multiple fluidic valve options

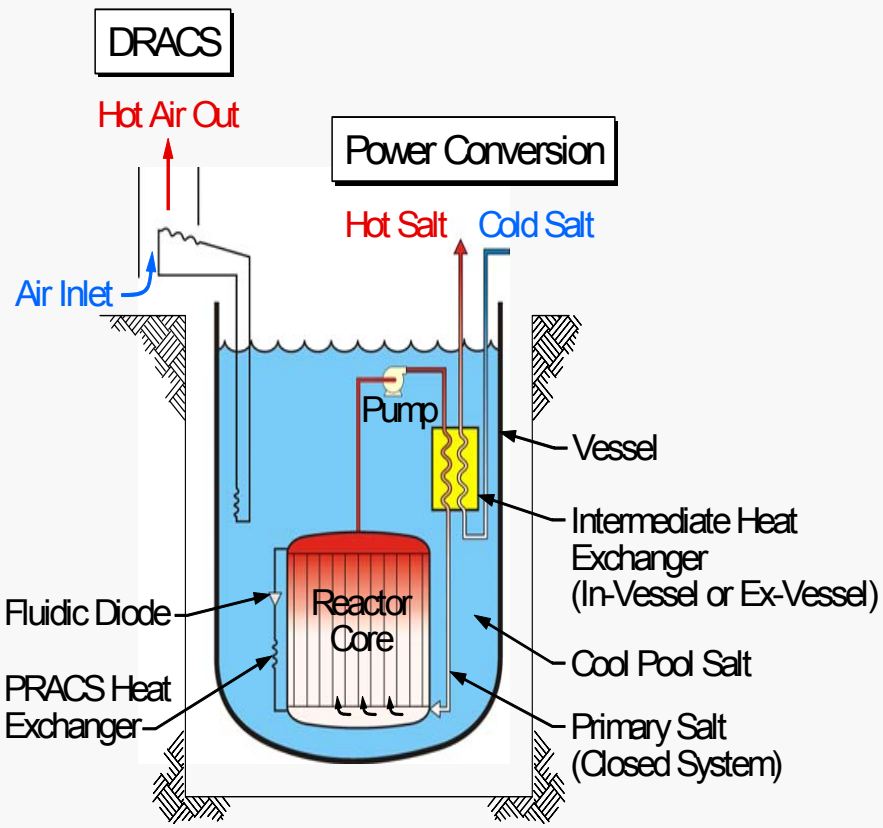


Initial Assessment of Alternative Decay-Heat-Removal Systems

Comparison of the Three Alternatives

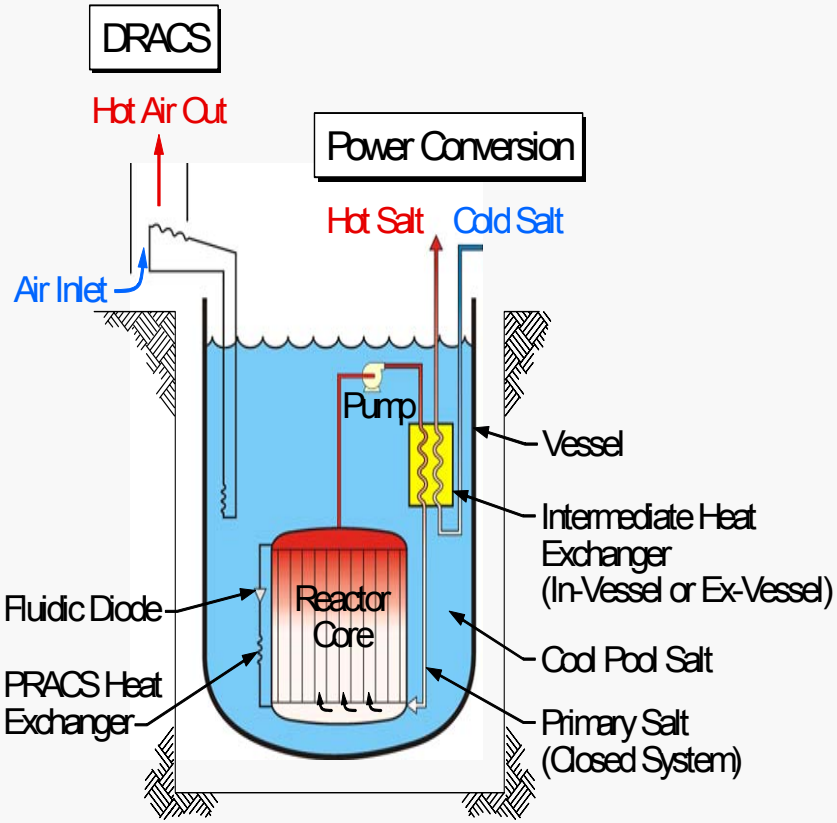
PRACS Enables the Design of Large Reactors [>4000 MW(t)]

- **Decay-heat-removal capability (DRACS) is a design choice**
  - **Not constrained by reactor vessel size (RVACS limit)**
- **Highest heat capacity in system made possible by use of cool pool salt**
  - **Minimum number of components at high temperature**
  - **Pool temperature not coupled to reactor coolant inlet temperature (unlike RVACS and DRACS)**



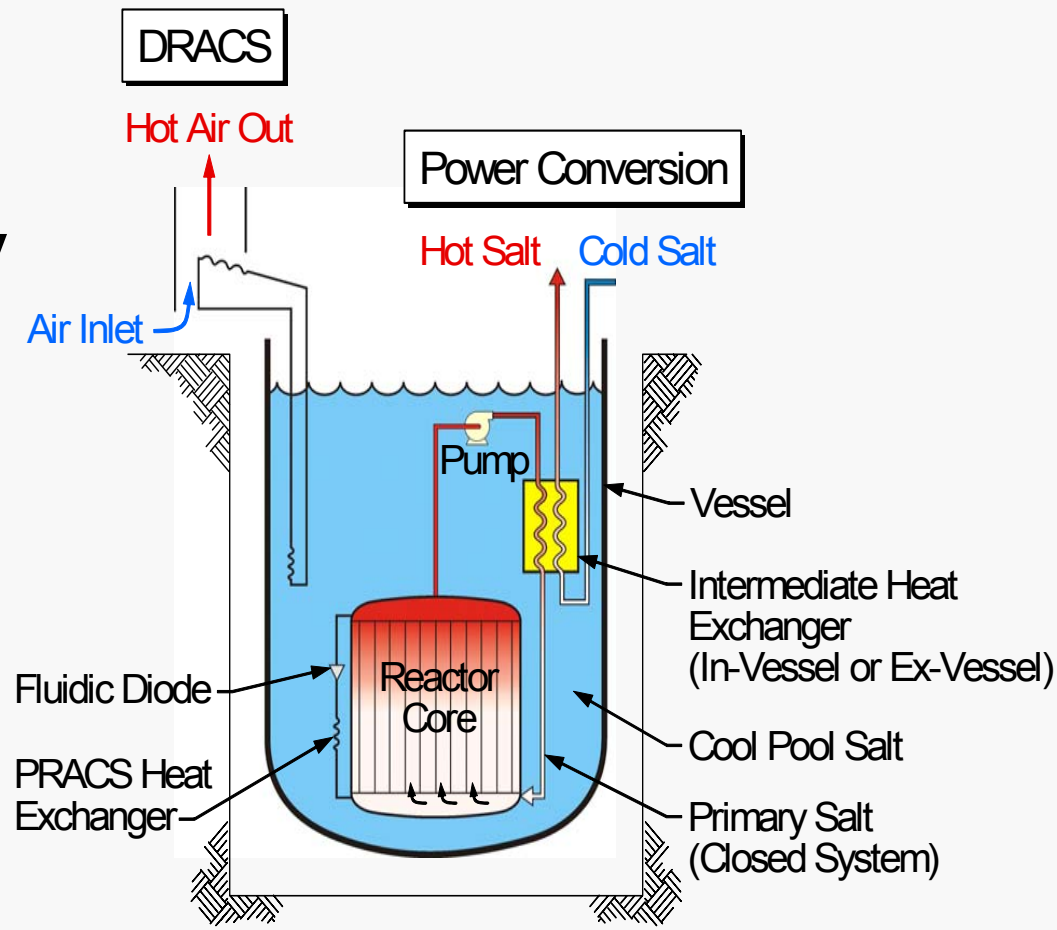
PRACS Enables Fast Core Shutdown in Response to Many Transients

- **Reactor core has a strong negative temperature coefficient (shuts down upon overheating)**
- **PRACS has a small primary system volume and heat capacity**
- **Loss of intermediate heat exchangers results in rapid increase in core temperature**
  - **Reactor shutdown if control rods not inserted**
  - **RVACS and DRACS options heat large salt volumes before core heat up**



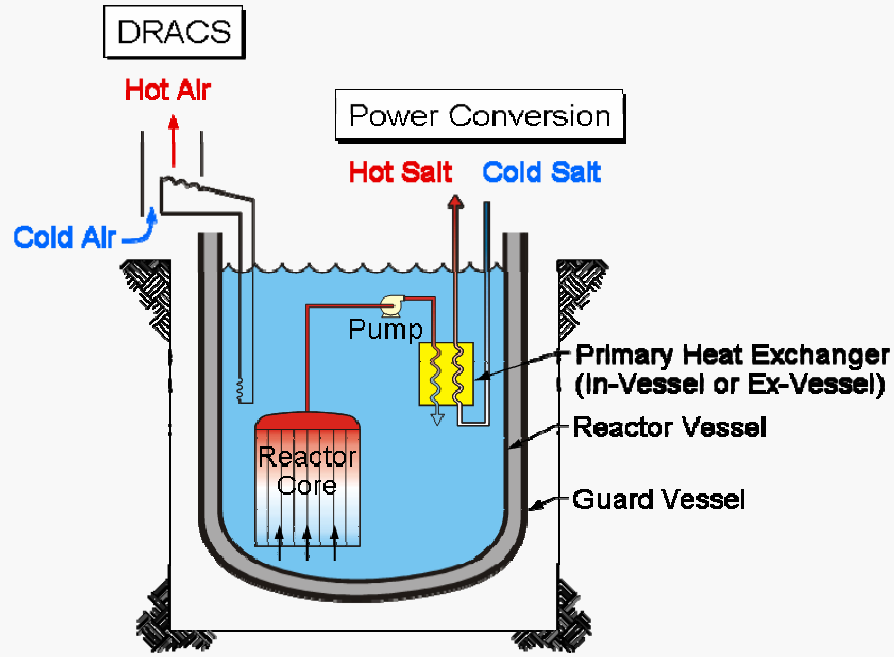
PRACS Minimizes Materials Challenges

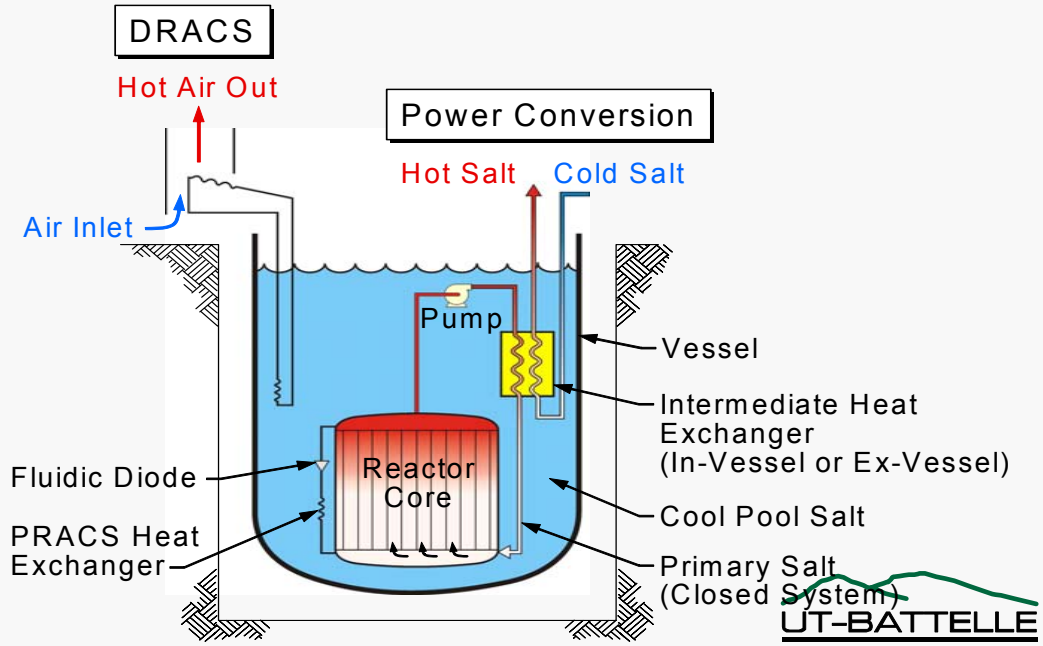
- **Minimum number of components at high temperature**
- **Primary-system boundary has cool salt on one side**
  - **Primary system has insulation or other features to minimize component temperatures**
  - **A safety concern is a primary-system failure due to high temperatures caused by insulation or by some other failure**
  - **Cold salt cools outside primary-system surfaces and protects against such events**



Modular Design of DRACS and PRACS is Advantageous

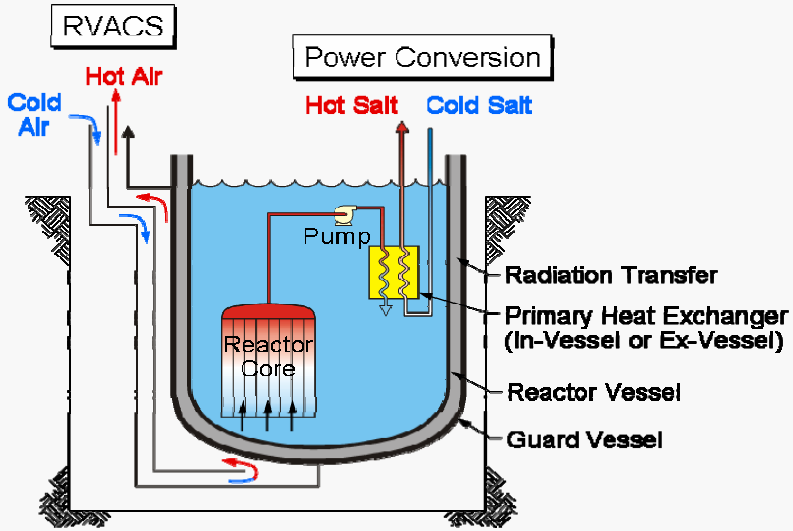
- **Full-scale module test is viable**
- **Simplified licensing by module testing**
- **Simplified scale-up from small to large reactors**

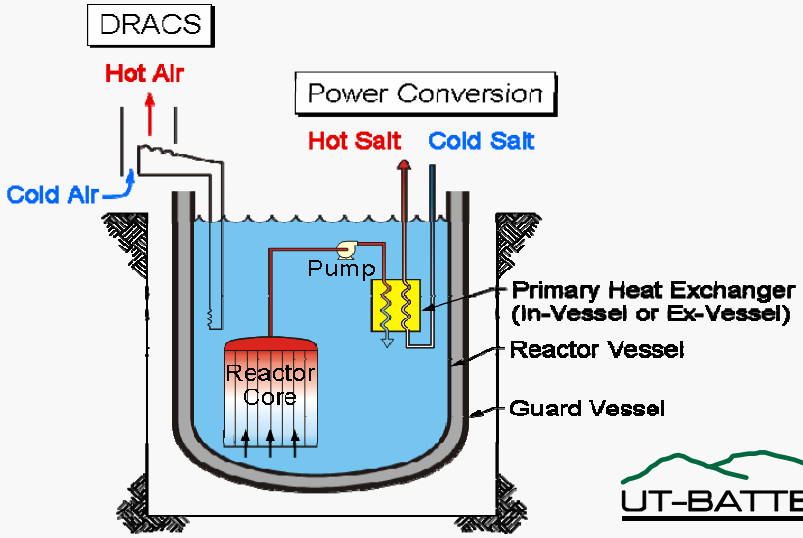




The Experience Base with RVACS and DRACS is Larger

- **RVACS and DRACS were developed for sodium-cooled reactors**
- **The major difference between the AHTR and sodium-cooled reactors is the temperature**
  - **SFR: ~550°C**
  - **AHTR: 700 to 950°C**





Conclusions

- **Three alternative AHTR passive decay-heat-removal systems identified**
  - **All viable**
- **Requirements drive design choices**
  - **AHTR to match or exceed modular gas-cooled reactor peak coolant temperatures and passive-safety decay-heat removal**
  - **Applicable to a large reactor**
  - **Minimize requirements for high-temperature components**
- **PRACS chosen as the base-case design for given set of requirements**
- **Significant R&D required**

Biography: Charles Forsberg

Dr. Charles Forsberg received his bachelor's degree in chemical engineering from the University of Minnesota and his doctorate in Nuclear Engineering from MIT. After working for Bechtel Corporation, he joined the staff of Oak Ridge National Laboratory, where he is presently a senior scientist. Dr. Forsberg is a fellow of the American Nuclear Society and received the 2002 ANS Special Award for Innovative Nuclear Reactors. He also received the 2005 American Institute of Chemical Engineers Nuclear Energy Division Robert E. Wilson Award for outstanding chemical engineering contributions to nuclear energy and the Oak Ridge National Laboratory Engineer of the Year Award in 2005 for his work on advanced high-temperature reactors. Dr. Forsberg has been awarded 10 patents and has published over 200 papers, many on advanced reactors, hydrogen, and repository systems.

Alternative Passive Decay-Heat Systems for the Advanced High-Temperature Reactor

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Abstract — *The Advanced High-Temperature Reactor (AHTR) is a low-pressure, liquid-salt-cooled high-temperature reactor for the production of electricity and hydrogen. The high-temperature (950°C) variant is defined as the liquid-salt-cooled very high-temperature reactor (LS-VHTR). The AHTR has the same safety goals and uses the same graphite-matrix coated-particle fuel as do modular high-temperature gas-cooled reactors. However, the large AHTR power output [2400 to 4000 MW(t)] implies the need for a different type of passive decay-heat-removal system. Because the AHTR is a low-pressure, liquid-cooled reactor like sodium-cooled reactors, similar types of decay-heat-removal systems can be used. Three classes of passive decay heat removal systems have been identified: the reactor vessel auxiliary cooling system which is similar to that proposed for the General Electric S-PRISM sodium-cooled fast reactor; the direct reactor auxiliary cooling system, which is similar to that used in the Experimental Breeder Reactor-II; and a new pool reactor auxiliary cooling system.*

These options are described and compared.